# Towards Improved CERES Angular Distribution Models

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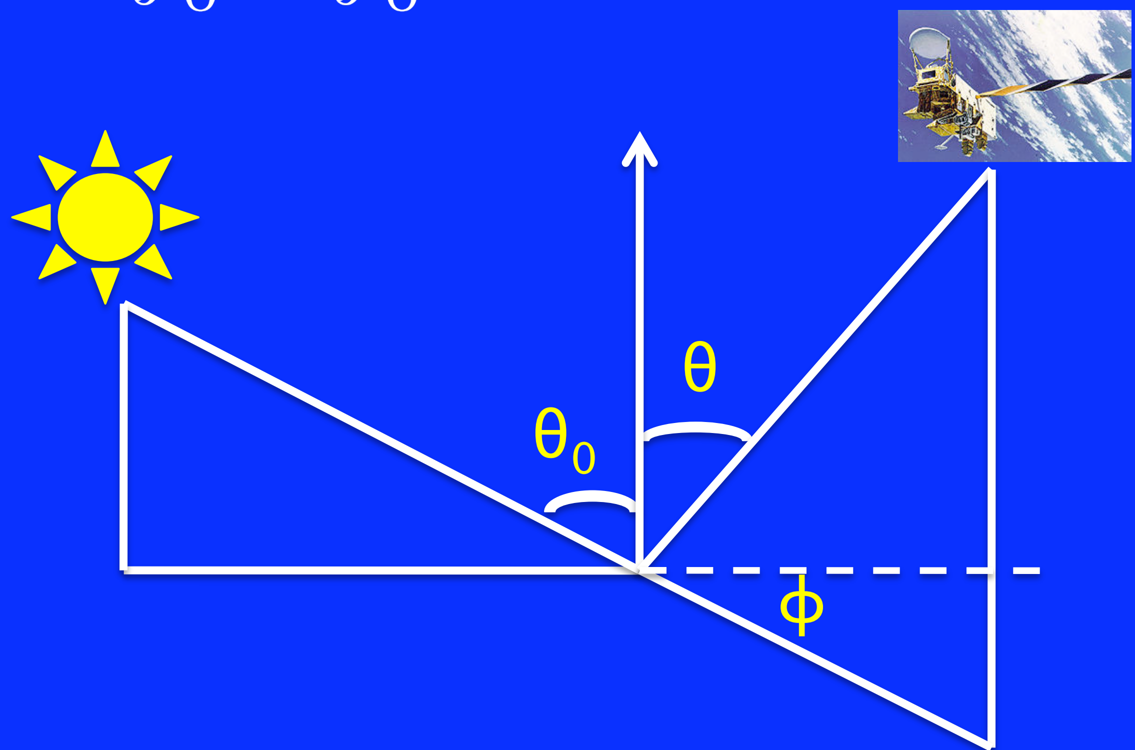
Thanks to Norman Loeb!

# Radiance and flux

- CERES measures radiance: $I(\theta_0, \theta, \phi)$
- Relationship between radiance and flux:

$$F(\theta_0) = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} I(\theta_0, \theta, \phi) cos\theta sin\theta d\theta d\phi$$



# The road from radiance to flux: angular distribution model

- Sort observed radiances into angular bins over different scene types;
- Integrate radiance over all θ and ϕ to estimate the anisotropic factor for each scene type;
- Apply anisotropic factor to observed radiance to derive TOA flux;

$$R(\theta_0,\theta,\phi) = \frac{\pi \hat{I}(\theta_0,\theta,\phi)}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \hat{I}(\theta_0,\theta,\phi) cos\theta sin\theta d\theta d\phi} = \frac{\pi \hat{I}(\theta_0,\theta,\phi)}{\hat{F}(\theta_0)}$$

$$F(\theta_0) = \frac{\pi I_o(\theta_0,\theta,\phi)}{R(\theta_0,\theta,\phi)}$$

# SW ADM for different scene types: Ed2 vs Ed4

| Scene | Ed2 | Ed4 |
|---|---|---|
| Clear Land | 1° regional monthly ADM using Ahmad&Deering 8-parameter fit; | 1° regional monthly ADM using modified RossLi 3-parameter fit; |
| Clear Ocean | Function of wind speed; correction for AOD; | Function of wind speed, AOD and aerosol types (maritime and dust); |
| Cloud Ocean | Continuous 5-parameter sigmoid function of ln(fτ) for three phases; | Update using the Ed2 method; |
| Cloud Land | Continuous 5-parameter sigmoid function of ln(fτ) for three phases; background albedo from clear land; | Update using the Ed2 method; |
| Fresh Snow | Snow fraction, surface brightness, cloud fraction, cloud optical depth; | 1° regional monthly ADM using RossLi 3-para fit for different NDVI for clear-sky; |
| Perm. Snow | Surface brightness, cloud fraction, cloud optical depth; | Snow index, cloud fraction, cloud optical depth; |
| Sea-Ice | Ice fraction, surface brightness, cloud fraction, cloud optical depth; | Sea ice index, cloud fraction, cloud optical depth; |

# LW ADM for different scene types: Ed2 vs Ed4

| Scene | Ed2 | Ed4 |
|---|---|---|
| Clear Ocean/Land | Discrete intervals of precip. water, lapse rate, skin temp. for six surface types; | Increase skin temp. intervals from 5 to 10 and add interpolation; |
| Cloudy Ocean/Land | Third-order polynomial fits between radiance and 'pseudoradiance' for intervals of precip. water, cloud fraction, surface skin temp. and sfc-cld temp. difference; | Interpolation between radiance and 'pseudoradiance' for intervals of precip. water, cloud fraction, surface skin temp. and sfc-cld temp. difference; |
| Fresh Snow | Discrete intervals of cloud fraction, surface skin temp., and sfc-cld temp. difference; | |
| Permanent Snow | Discrete intervals of cloud fraction, surface skin temp., and sfc-cld temp. difference; | |
| Sea-Ice | Discrete intervals of cloud fraction, surface skin temp., and sfc-cld temp. difference; | |

# Predicted radiance vs. observed radiance

$$R(\theta_0,\theta,\phi) = \frac{\pi \hat{I}(\theta_0,\theta,\phi)}{\hat{F}(\theta_0)} \qquad F(\theta_0) = \frac{\pi I_o(\theta_0,\theta,\phi)}{R(\theta_0,\theta,\phi)}$$

$$F(\theta_0) = \frac{I_o(\theta_0,\theta,\phi)}{\hat{I}(\theta_0,\theta,\phi)}\hat{F}(\theta_0)$$

- Predicted radiances can be used to verify the accuracy of ADM;

# Normalize predicted and observed radiance

Observed radiance:

$$I_j^o, \quad j = 1, \cdots, n$$

1°

Predicted radiance:

$$\hat{I}_j, \quad j = 1, \cdots, n$$

1°

$$\overline{I^o} = \frac{1}{n}\sum_{j=1}^{n} I_j^o \qquad \bar{\hat{I}} = \frac{1}{n}\sum_{j=1}^{n} \hat{I}_j$$

$$RMS = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(\frac{\hat{I}_j}{\bar{\hat{I}}} - \frac{I_j^o}{\overline{I^o}}\right)^2}$$

- RMS error between normalized predicted radiance and normalized observed radiance is closely related to the ADM error
- RMS error of 10% (20%) corresponds to flux RMS error of about 2~12 (4~15) $Wm^{-2}$ over different scene types based upon theoretical simulations

# Angular distribution model over clear land/desert

| Scene | Ed2 | Ed4 |
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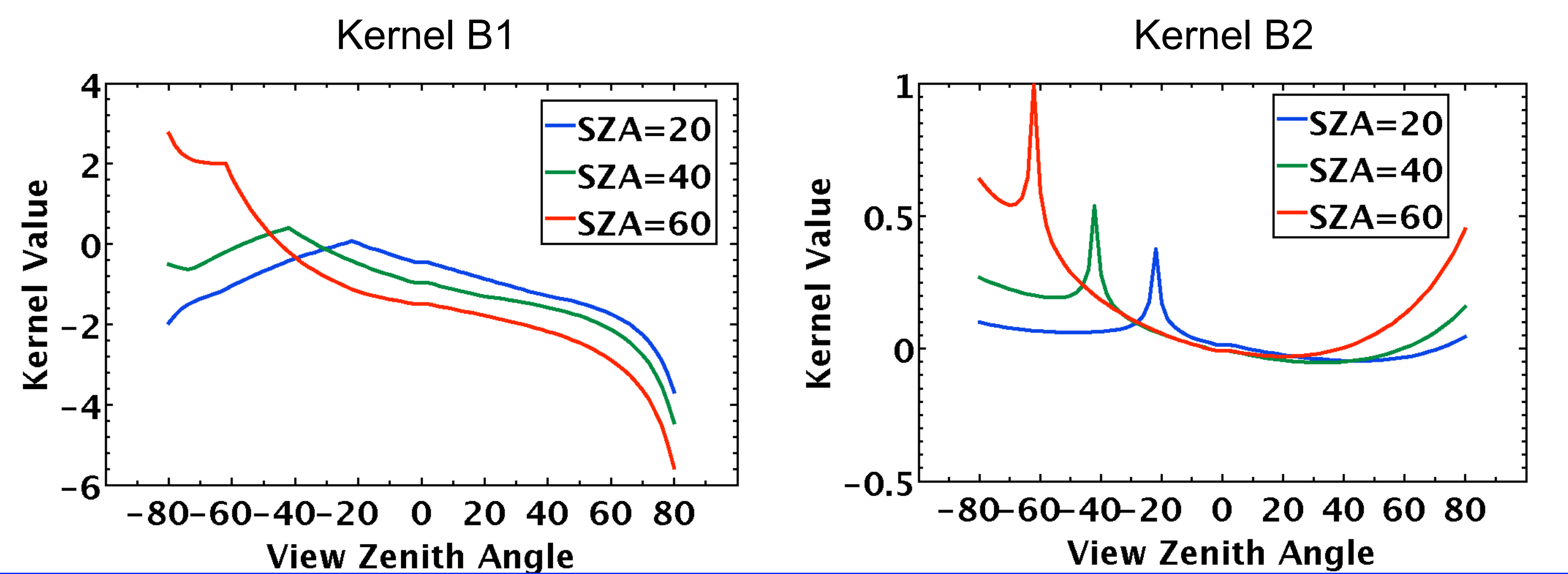
# A simpler BRDF model for clear-sky land: Modified RossLi

- B1 estimates the directional reflectance of a flat surface with randomly distributed and oriented protrusions;
- B2 approximates the radiative transfer within a vegetation canopy, accounts for the hot spot effect;

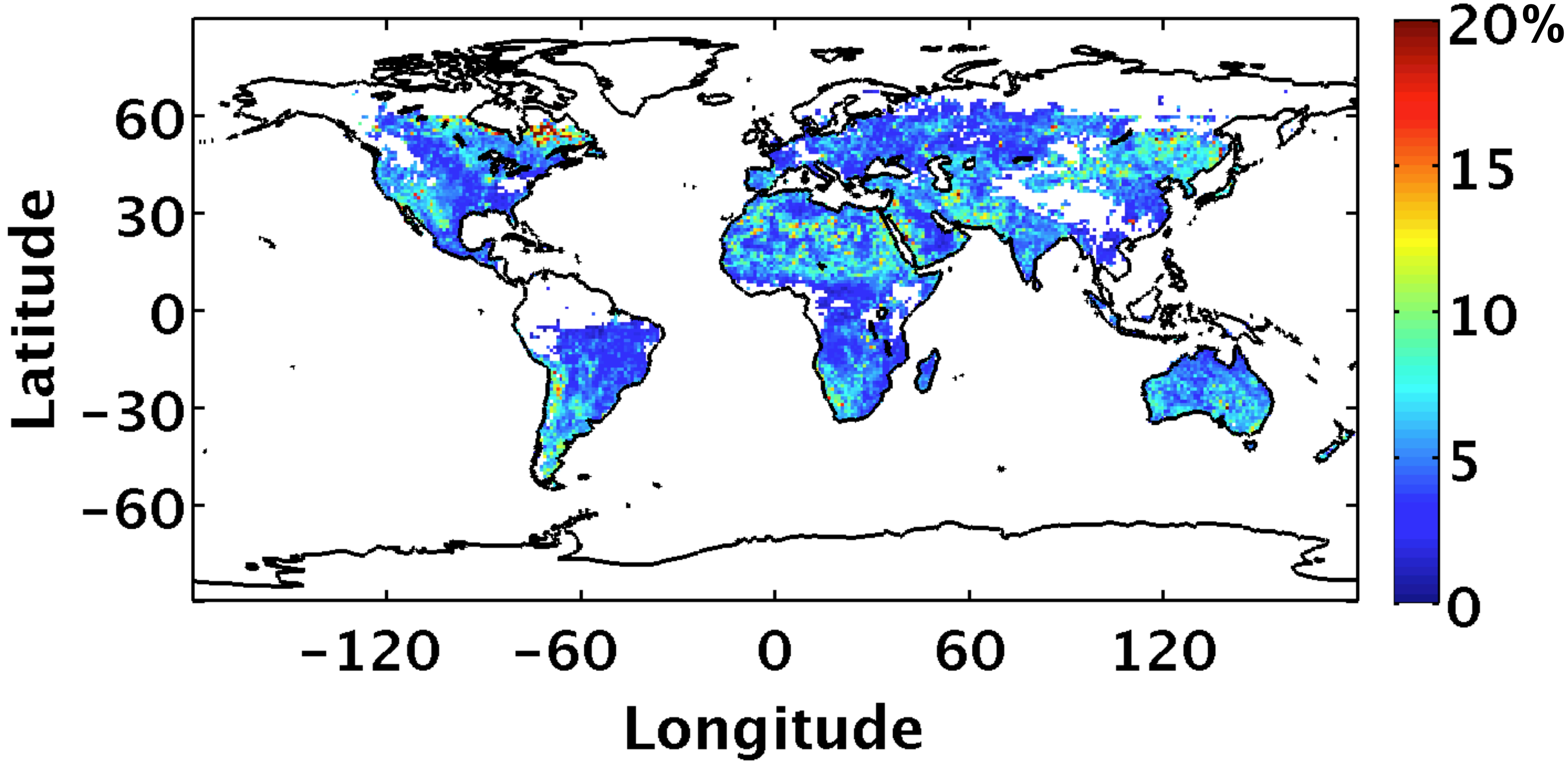
$$\rho(\mu_0, \mu, \phi) = k_0 + k_1 \cdot B_1(\mu_0, \mu, \phi) + k_2 \cdot B_2(\mu_0, \mu, \phi)$$

from Maignan et al., 2004



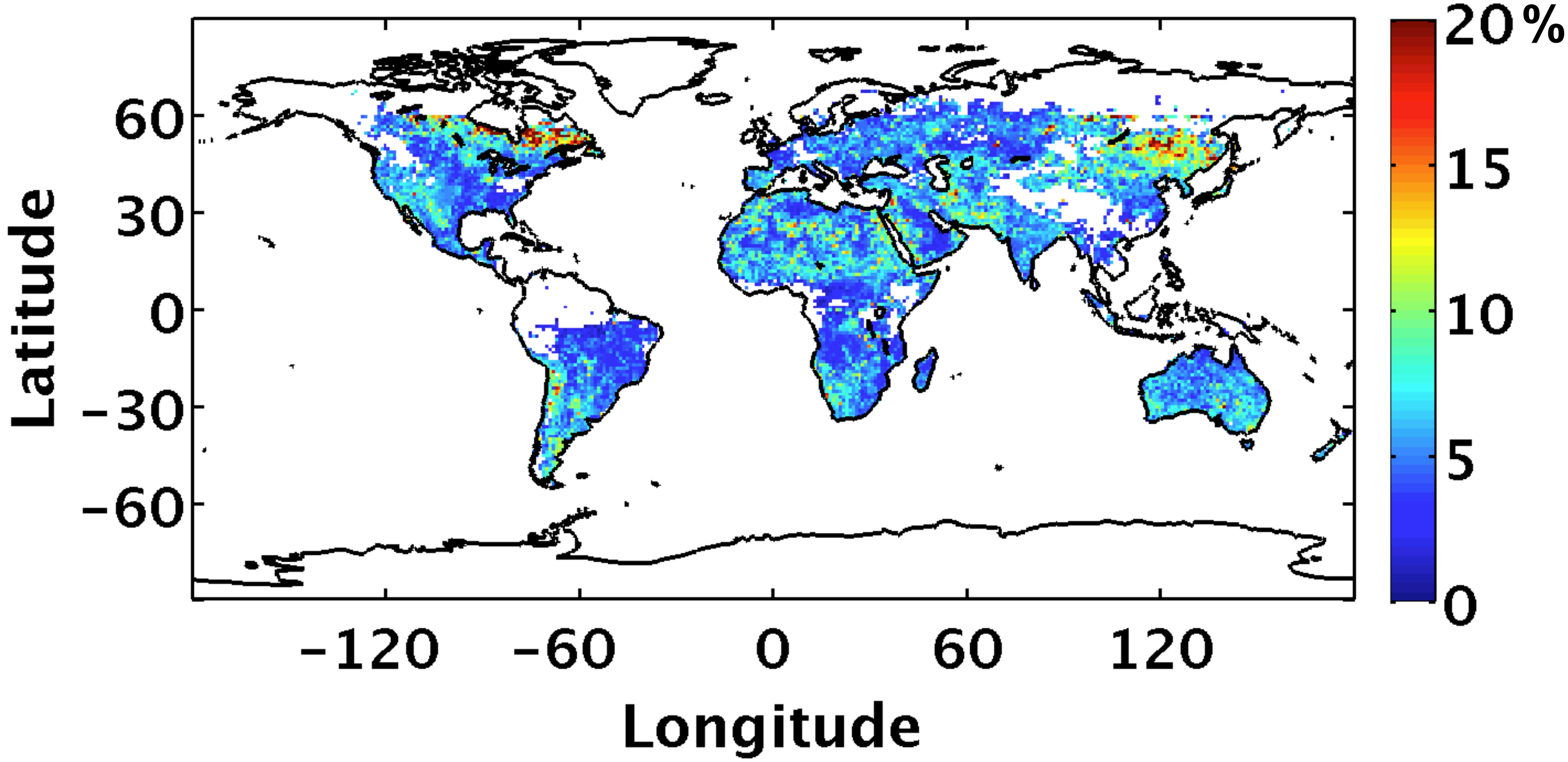
# Modified RossLi BRDF model reduces the RMS error

RMS error (%) using prototype Ed4 ADM for 200305 FM2
over clear-sky land/desert: Mean RMS error = 5.5%



# Modified RossLi BRDF model reduces the RMS error

RMS error (%) using Ed2 ADM for 200305 FM2
over clear-sky land/desert: Mean RMS error = 6.1%



# SW angular distribution model over clear ocean

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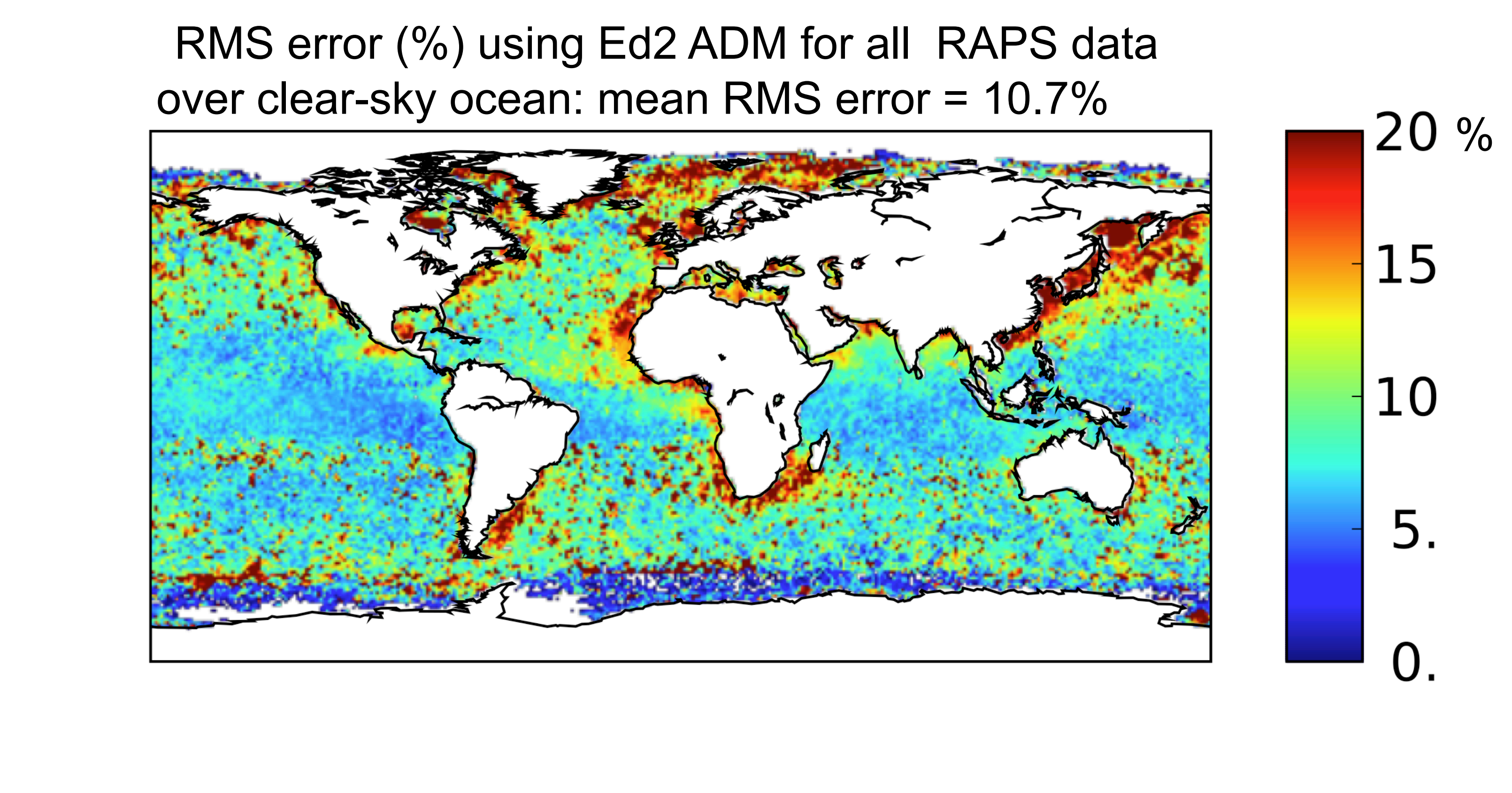
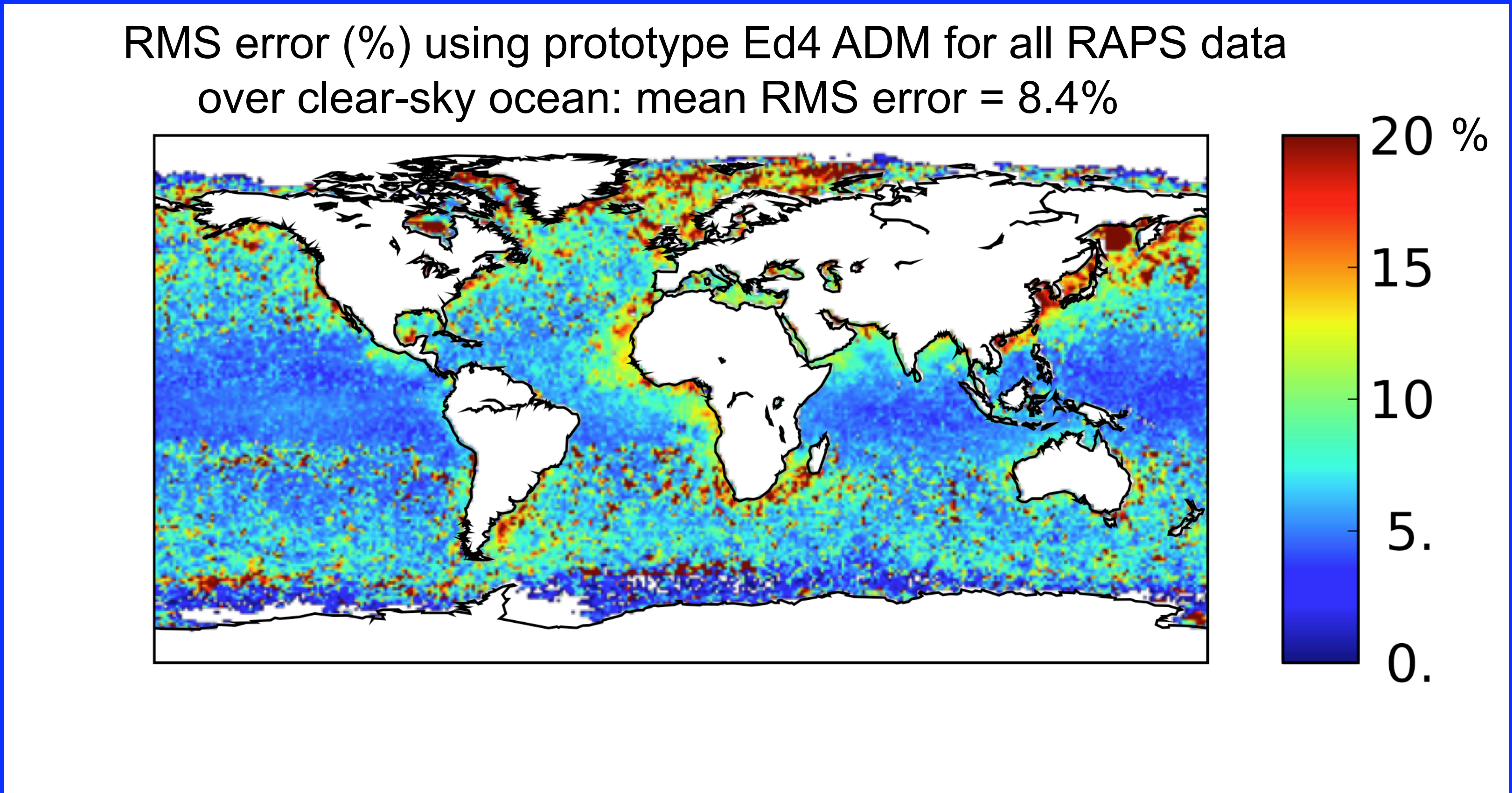
# Clear-sky angular distribution model over ocean

- Clear-sky ADM over ocean $R(w, \theta_0, \theta, \phi)$;
- Aerosol optical depth was not directly considered, ADM dependence on aerosol optical depth is implicitly accounted for by theoretical adjustment.

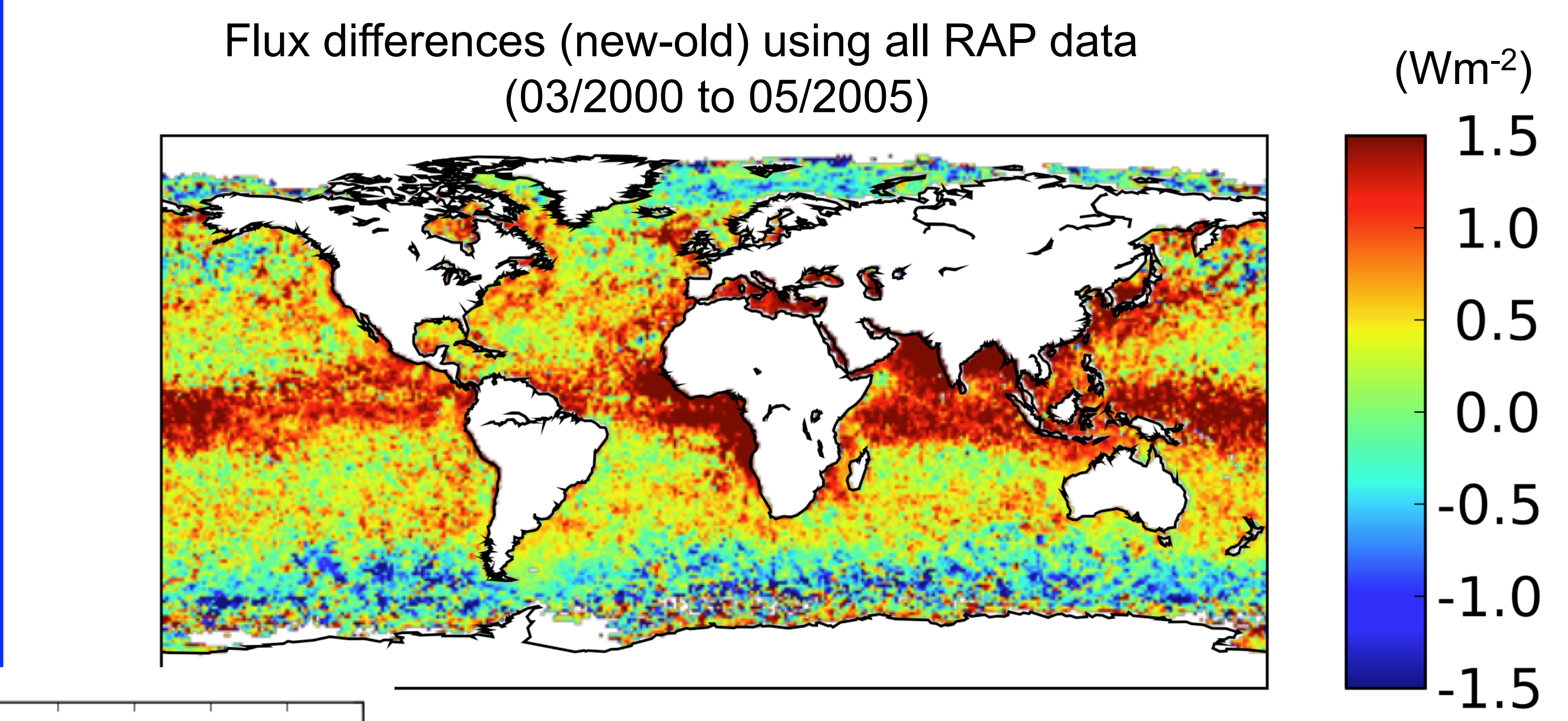


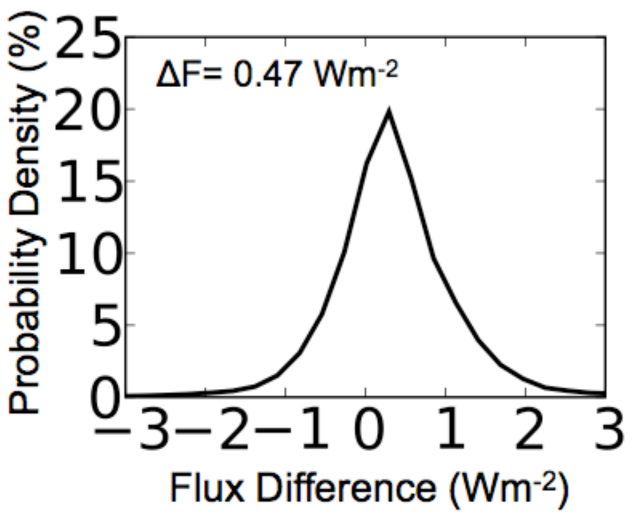
# New clear-sky ADM accounts for aerosol loading and type

- Develop a two-channel (0.64 and 0.86 μm) AOD retrieval using maritime and dust aerosols;
- Stratify AOD into bins (2 for maritime and 3 for dust);
- Build ADM for each AOD bin and type separately (5 ADMs).



# New clear-sky ocean ADM increases the instantaneous TOA flux by 0.5 $Wm^{-2}$



# Angular distribution model over cloudy ocean

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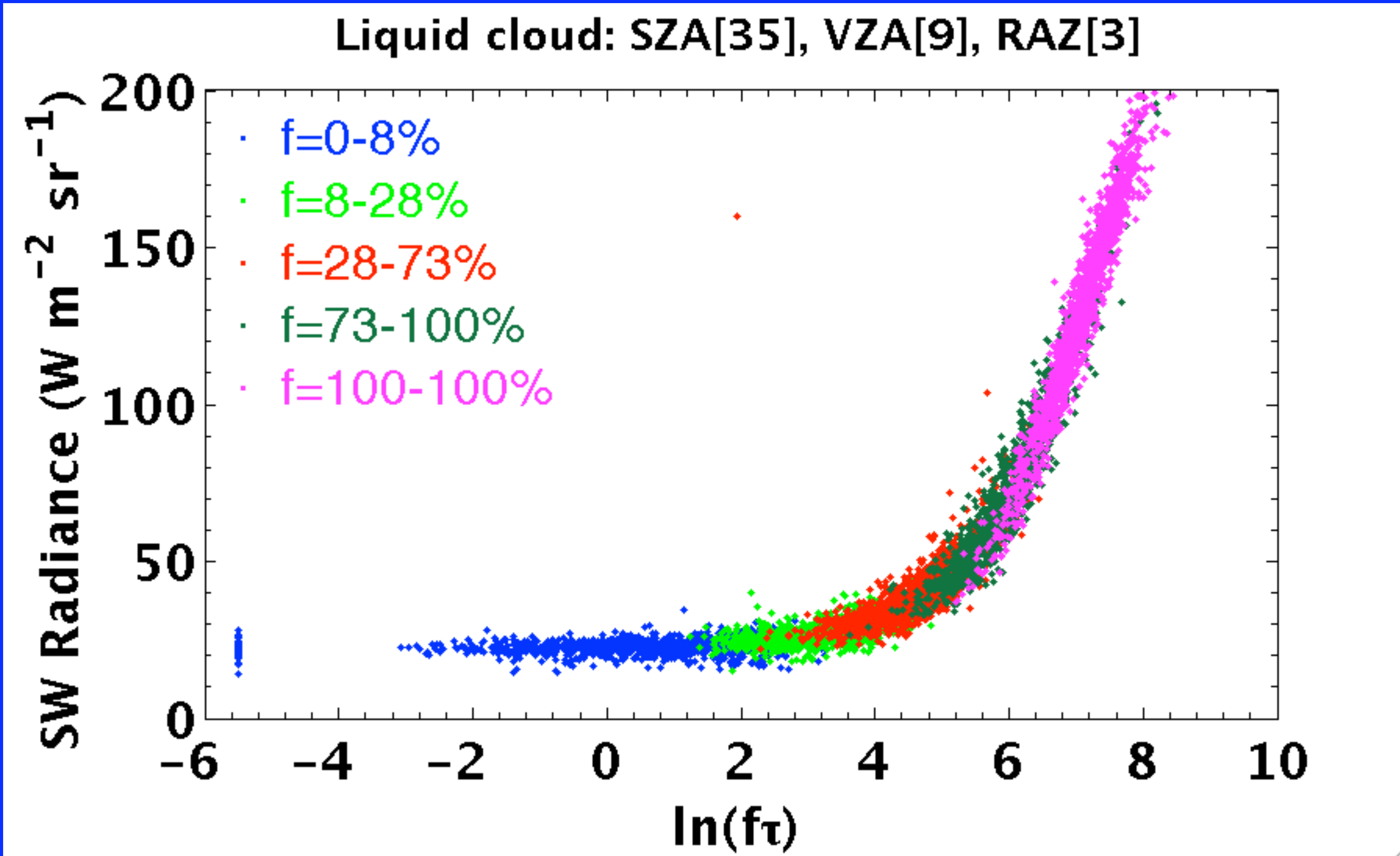
# Angular distribution model over cloudy ocean

- For glint angle > 20°, or glint angle < 20° and ln(fτ) > 6:
  - Average instantaneous radiances into 750 intervals of ln(fτ);
  - Apply a five-parameter sigmoidal fit to mean radiance and ln(fτ);

$$I = I_0 + \frac{a}{[1 + e^{-(x-x_0)/b}]^c}$$

- For glint angle < 20° and ln(fτ) < 6:
  - Calculate mean radiance for 6 wind speed bins and 4 ln(fτ) bins;
  - Use mean radiance to build ADM

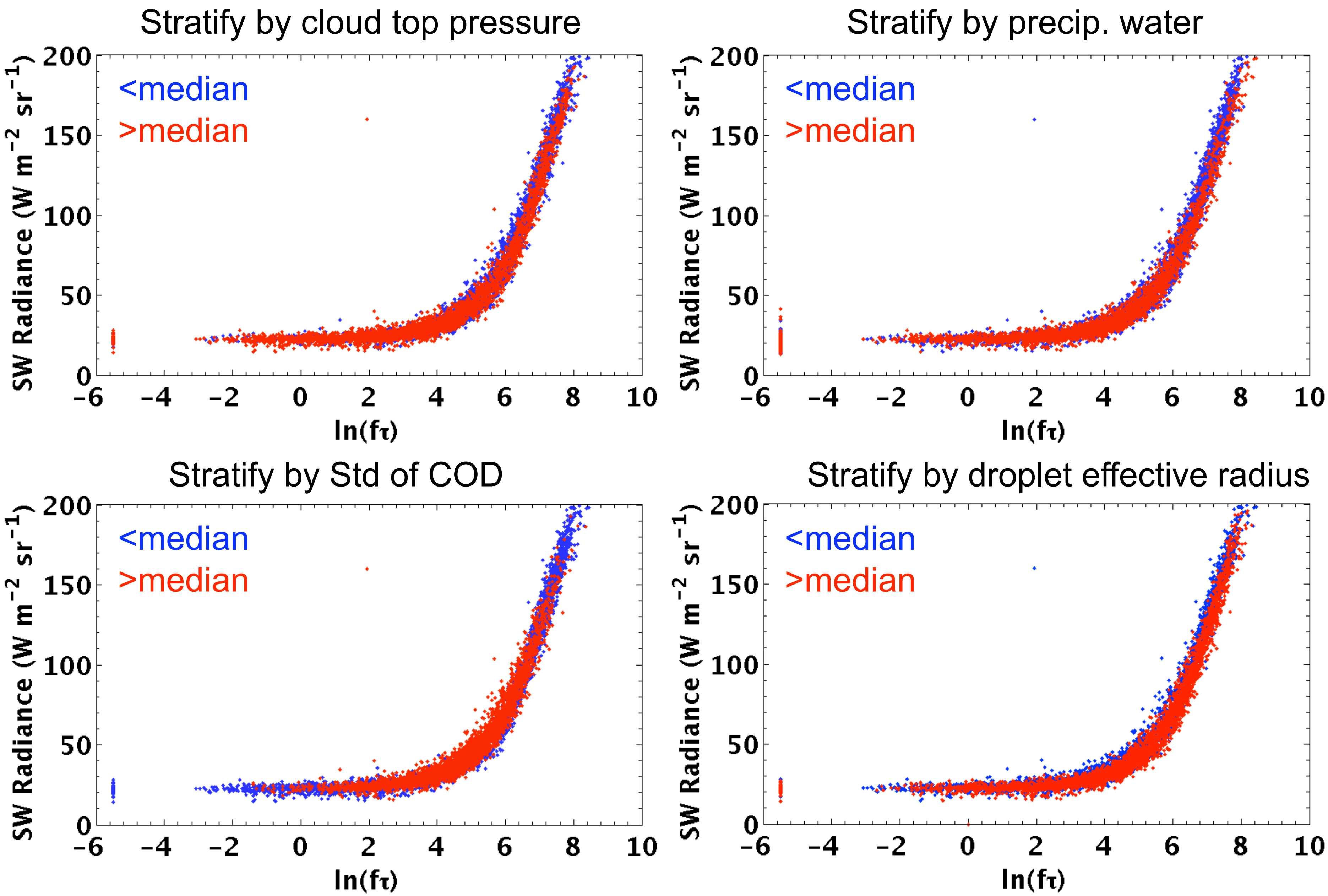
# A case of sigmoidal fit over ocean



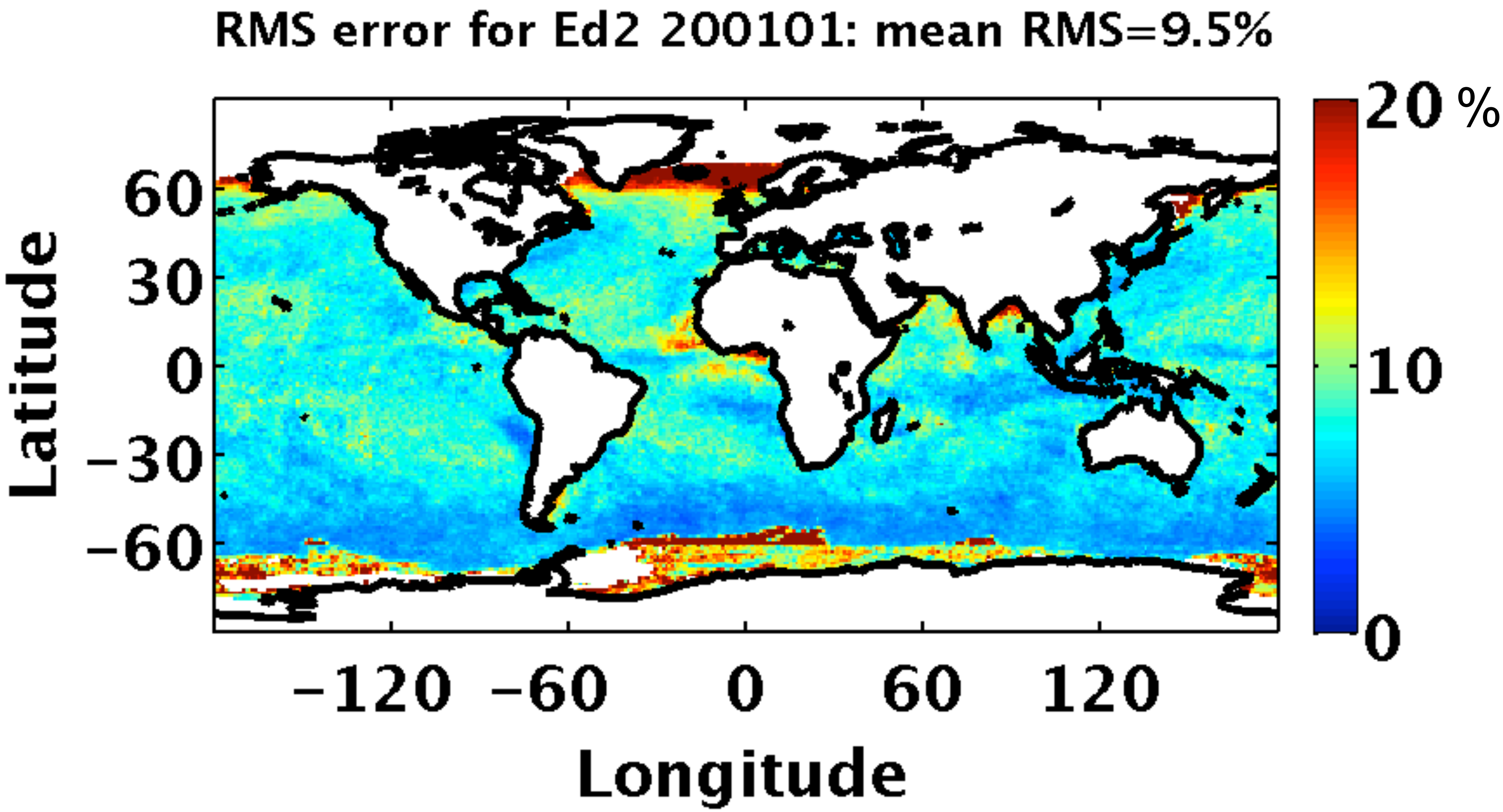
# Do we need to consider other variables to define the ADM?

- Current ADM considers cloud optical depth, cloud fraction, and cloud phase;
- Are there any other variables that we need to consider?
  - Cloud top pressure
  - Cloud droplet size
  - Standard deviation of cloud optical depth
  - Precipitable water

# Sigmoidal fit is not sensitive to other variables



# RMS error between normalized predicted and measured radiance



# Angular distribution model over cloudy land/desert

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# Angular distribution model over cloudy land/desert

- Derive cloudy area contribution from observed radiance:

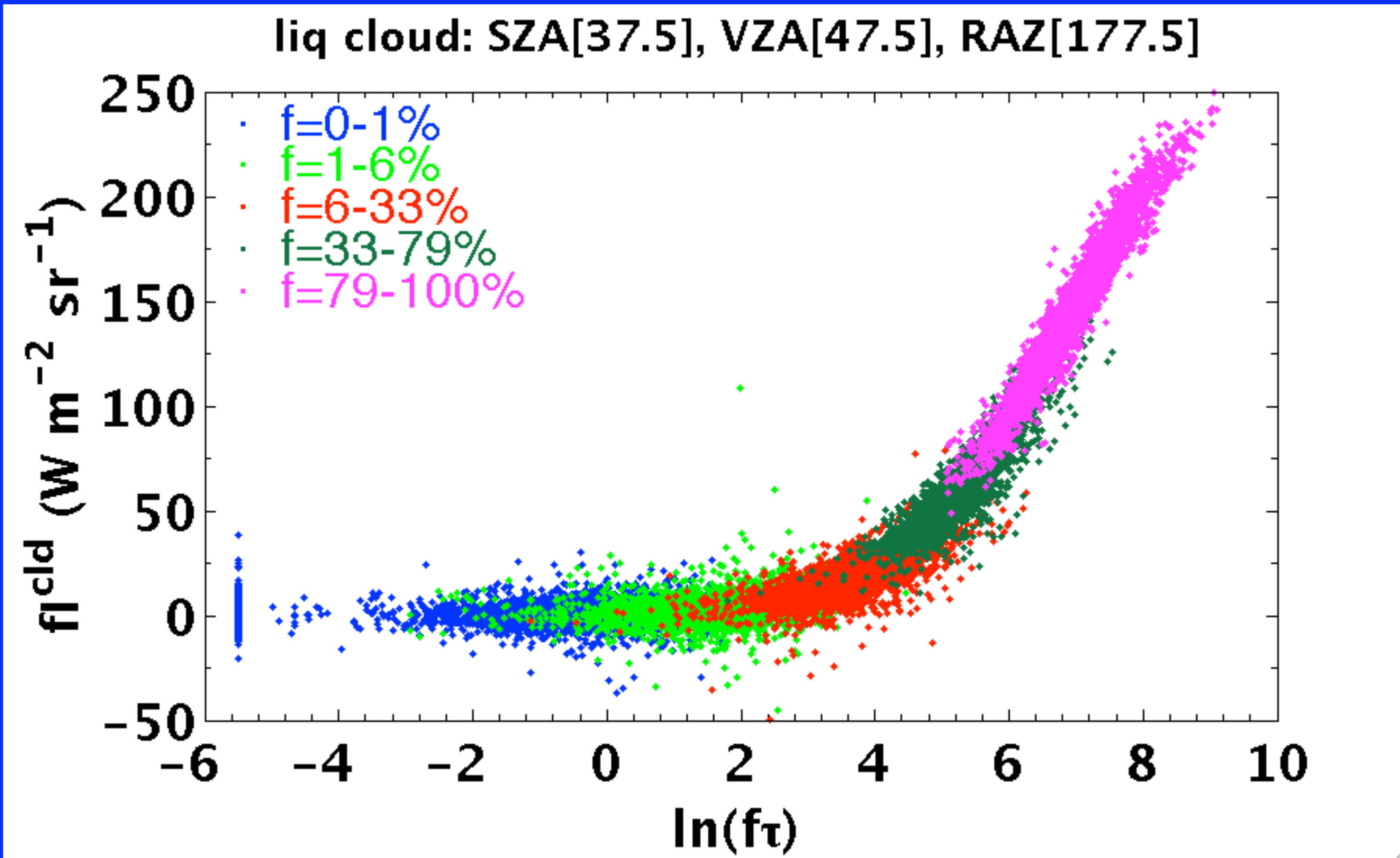
$$f I^{cld}(\mu_0,\mu,\phi) = I(\mu_0,\mu,\phi) - (1-f)\frac{\mu_0 E_0}{\pi}\rho^{clr}(\mu_0,\mu,\phi) - f\frac{\mu_0 E_0}{\pi}\left[\rho^{clr}(\mu_0,\mu,\phi)e^{\frac{-\tau}{\mu_0}}e^{\frac{-\tau}{\mu}} + \overline{\alpha}^{clr}\frac{t^{cld}(\tau,\mu_0)t^{cld}(\tau,\mu)}{1-\overline{\alpha}^{clr}\overline{\alpha}^{cld}(\tau)}\right]$$

- Average instantaneous $fI^{cld}$ into 375 intervals of $\ln(f\tau)$ for each angular bin (5°) for three cloud phases;

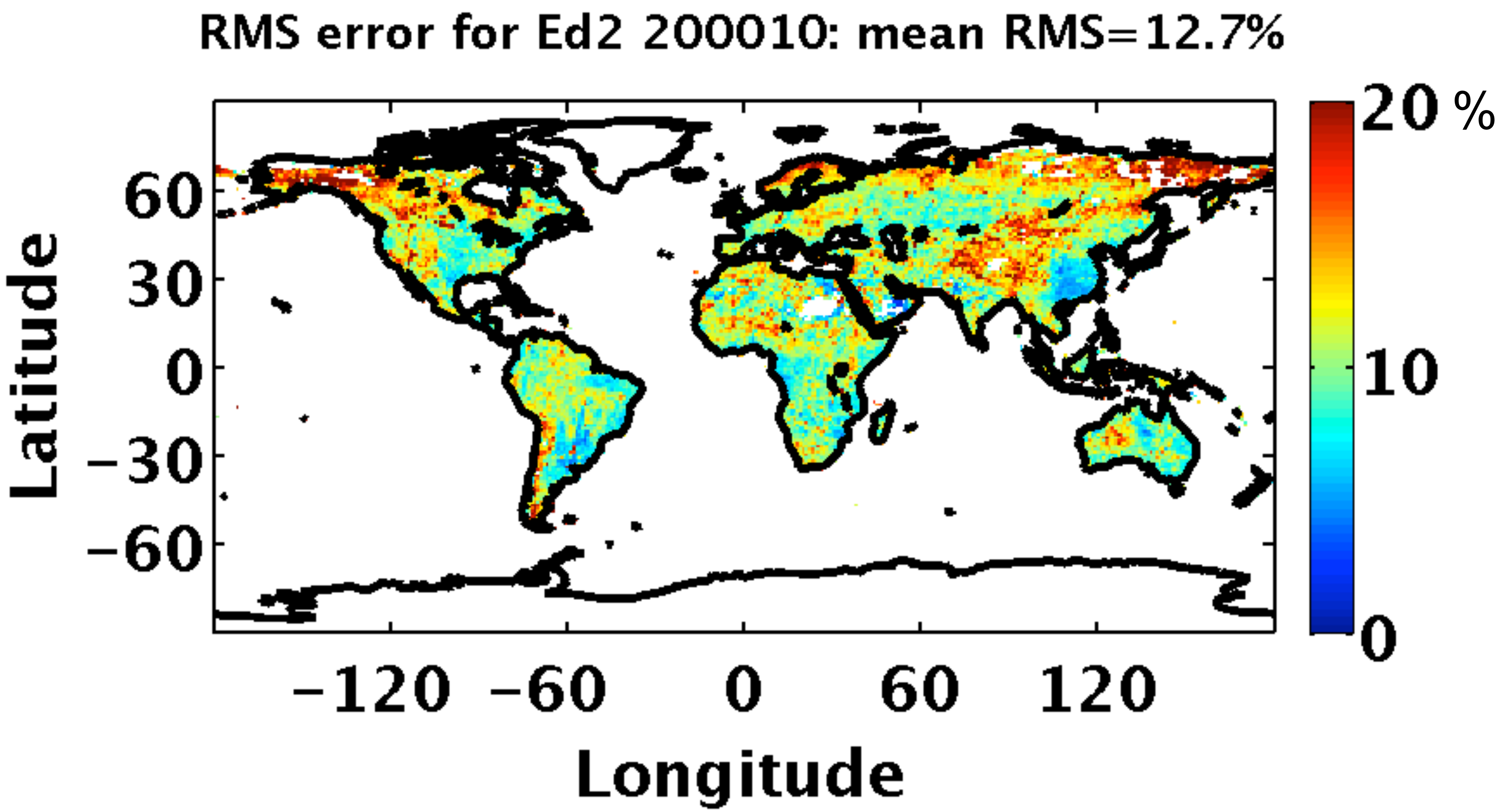
- Apply a five-parameter sigmoidal fit to mean $fI^{cld}$ and $\ln(f\tau)$;

$$I = I_0 + \frac{a}{[1+e^{-(x-x_0)/b}]^c}$$

# A case of sigmoidal fit over land



# RMS error between normalized predicted and measured radiance



# SW angular distribution model over permanent snow

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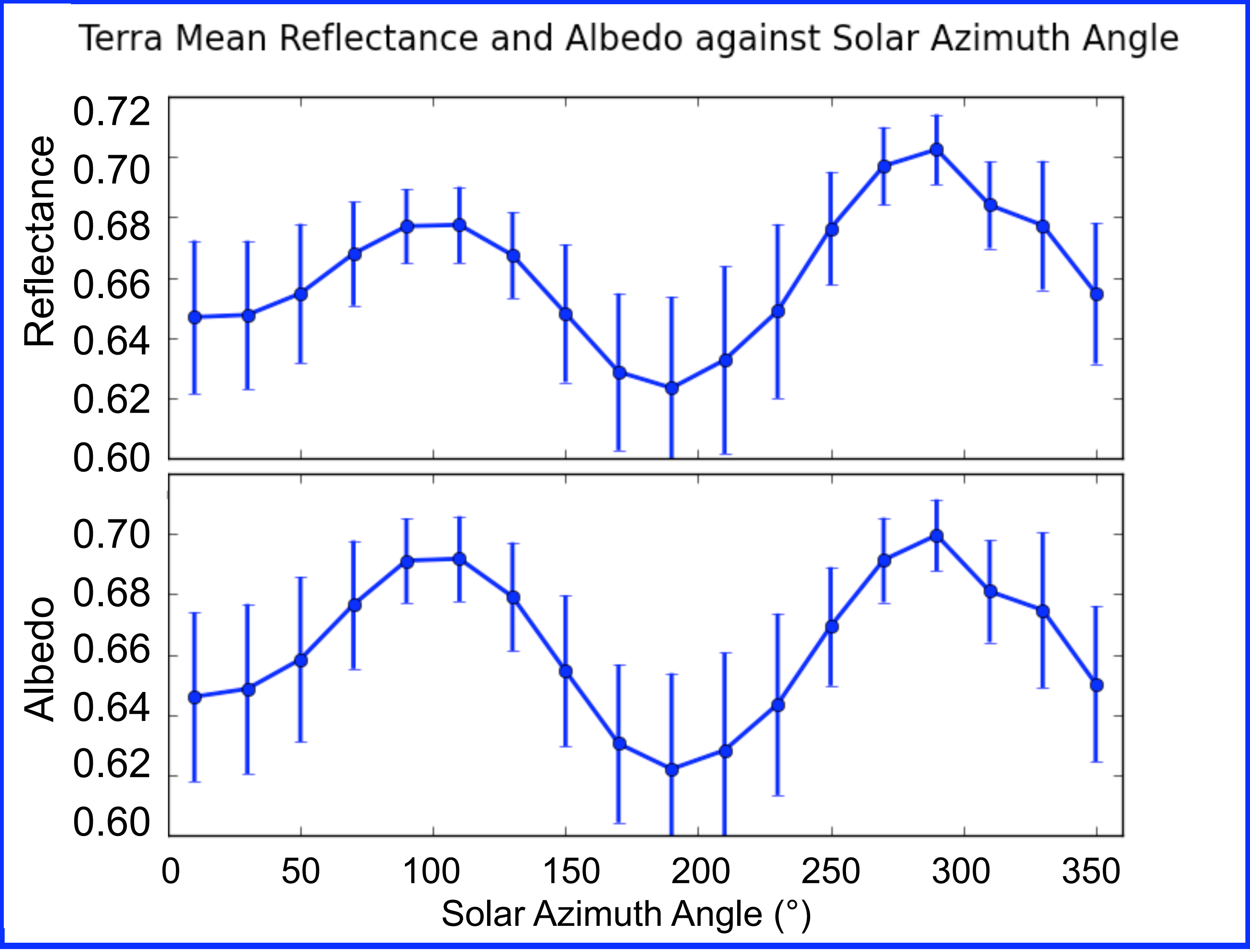
# Why reflectance and albedo are sensitive to solar azimuth?

- Use Dec. clear-sky data over south pole (88~89S, -93~-101W);
- Angular bins: SZA [65~70]; VZA [55~70]; RAZ [60~70];



# Permanent snow surface is not flat: sastrugi

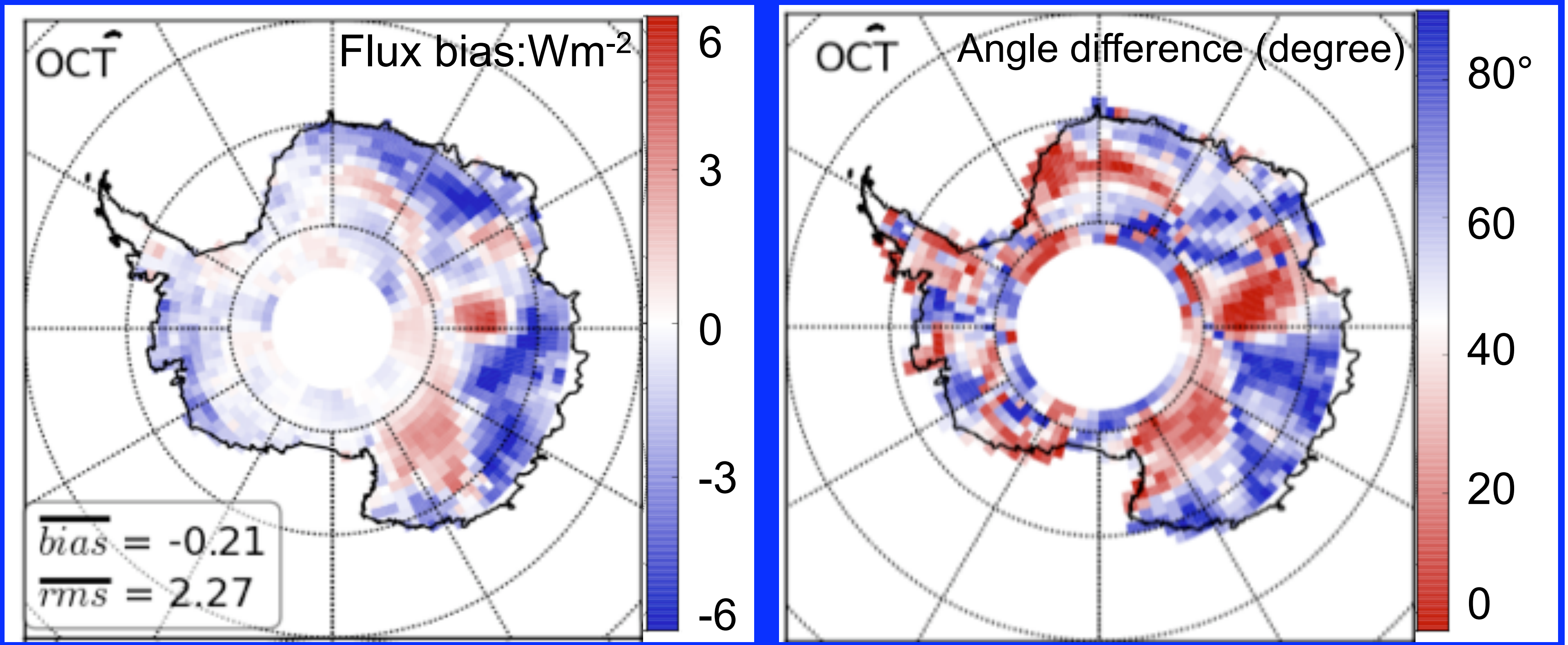
- Sastrugi: An irregularity formed by the wind on a snow plain. "Snow wave" is not completely descriptive, as the sastrugi has often a fantastic shape unlike the ordinary conception of a wave (from Scott's Last Expedition);
- Sastrugi generally aligned parallel to prevailing wind direction, but sometimes two or three sets of sastrugi crossing each other.


Image from homelessHeidi


Bill McAfee

# Regional clear-sky flux bias and the orientation of sastrugi

- Flux bias: $F(\theta_v) - F(\theta_v < 20^\circ)$
- Difference between most frequent wind direction and solar azimuth angle
- Positive flux bias when wind direction is parallel to solar azimuth and negative flux bias when wind direction is perpendicular to solar azimuth



# LW angular distribution model over clear ocean/land

| Scene | Ed2 | Ed4 |
|---|---|---|
| Clear Ocean/Land | Discrete intervals of precip. Water (4), lapse rate (4), skin temp. (5) for six surface types; | Increase skin temp. intervals from 5 to 10 and add interpolation; |
| Cloudy Ocean/Land | Third-order polynomial fits between radiance and 'pseudoradiance' for intervals of precip. water, cloud fraction, surface skin temp. and sfc-cld temp. difference; | Interpolation between radiance and 'pseudoradiance' for intervals of precip. water, cloud fraction, surface skin temp. and sfc-cld temp. difference; |
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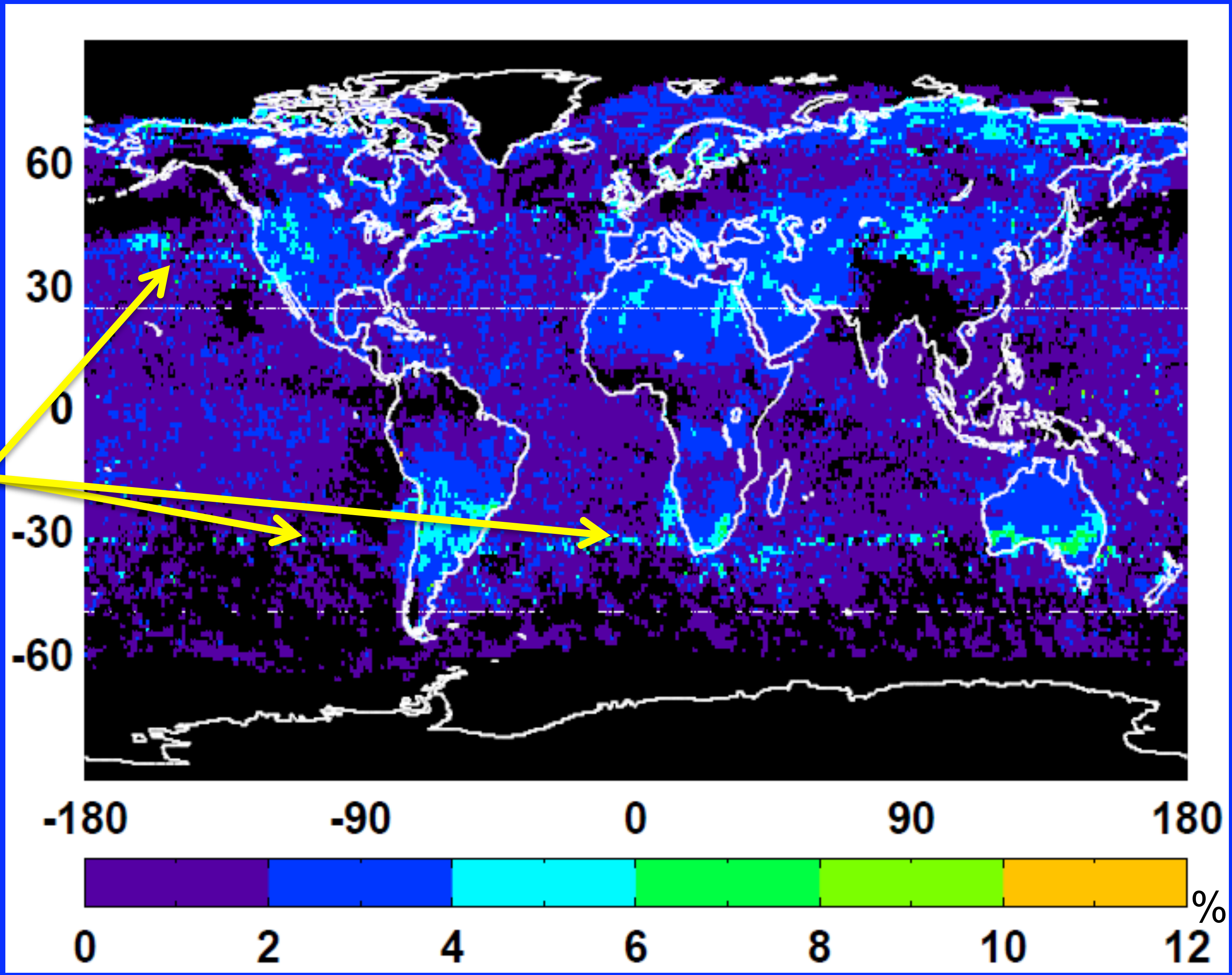
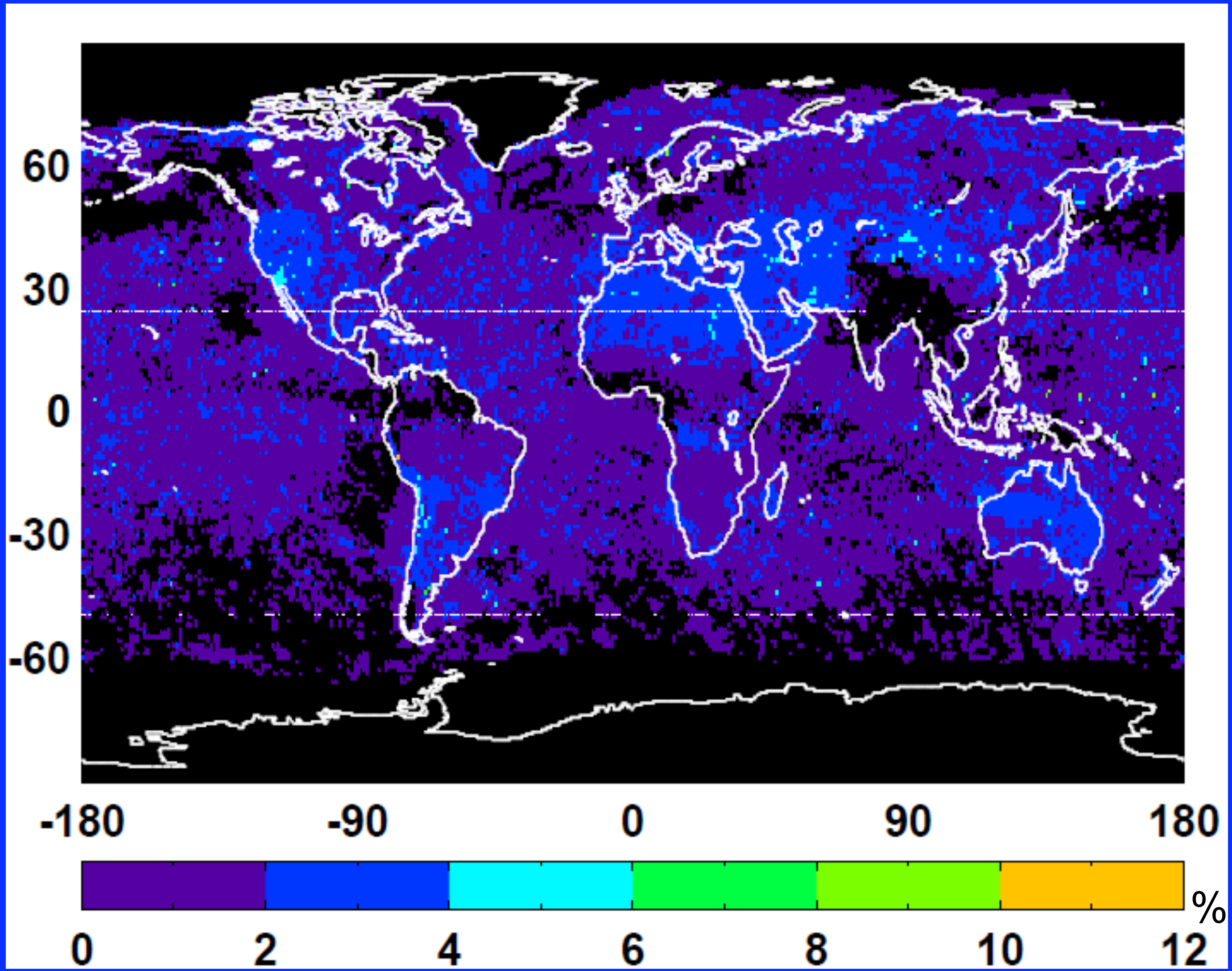
# RMS error between normalized predicted and measured radiance: July 2000 daytime (Ed2)

High errors over oceans near Ts=290K boundary



# Increase surface temperature bins + interpolation reduces the RMS error: July 2000 daytime



# More talks on ADM

Co-I talk by Joe Corbett on Thursday
"The Effect of Sastrugi on TOA Albedos from CERES"

Working group talk by Zach Eitzen
"Progress in clear-sky Longwave ADMs"

Working group talk by Lusheng Liang
"Impact of Aerosol Type on CERES Clear-sky Shortwave ADM over Ocean"

## Schedule

- Edition 4 SSF?
- Deliver Edition 4 ADM a year after Edition 4 SSF in production (possible but optimistic goal) !

# Summary

- Thorough evaluation of SW cloudy-sky ADM indicates that the five-parameter sigmoidal fit is sufficient;
- Aerosol optical depth/type classified clear ocean ADMs reduce the RMS error between predicted and observed radiances from 10.7% to 8.4% ;
- Uncertainty in TOA SW fluxes from sastrugi over Antarctic:
  - Monthly-mean: clear-sky < 5 $Wm^{-2}$ ; all-sky < 2 $Wm^{-2}$ ;
  - Annual-mean all-sky ~0.0 $Wm^{-2}$;
- For LW clear-sky over ocean/land, increasing surface temperature bins and adding interpolation reduce the RMS error between normalized predicted and observed radiances from 1.8% to 1.4%.